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A bobber's perspective on angler-driven vectors of invasive species transmission

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Abstract

Prevention of aquatic invasive species is a fundamental management challenge. With hundreds of millions of people participating in fishing trips each year, understanding angler movements that transmit invasive species can provide critical insight into the most effective locations and scales at which to apply preventative measures. Recent evidence suggests that mobile technologies provide new opportunities to understand different types of angler movement behaviour beyond what is possible with infrequently and sparsely conducted in-person boat surveys and mail questionnaires. Here we capitalise on data provided by ReelSonar's iBobber, a sonar-enabled bobber with over 5 M recorded fishing locations, globally. By quantifying geographic patterns of fishing activities and assessing how these patterns change seasonally, we explore angler behaviour across the entire continental United States in terms of fishing frequency and distance travelled between sites and characterise the attributes of fished ecosystems. We found that iBobber users (anglers) undertook 66,918 trips to 20,049 different water-bodies over a two-year period. Anglers who use iBobber were more likely to visit larger, deeper and more urbanised water-bodies and these water-bodies were over five times more likely to be a reservoir compared to a lake. Inter-water-body travel road distances averaged 93 km (SD = 277 km; range < 1–300 km) and nearly half of these movements occurred over a timespan of two days or less, a timeframe that we show falls well within the desiccation tolerance window of many prevalent plant and animal invasive species. Our study offers novel insight into spatiotemporal patterns of angler behaviour well beyond the geographical and temporal extent of conventional ground-collected approaches and carries important implications for predicting and preventing future transmission of aquatic invasive species via recreational fishing.

Keywords

big data, desiccation tolerance, invasion risk, recreational fishing, species transmission, vectors

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Introduction

Technological innovations in ecology have evolved significantly in recent decades, now serving a much more common and indispensable role in scientific research and management. The application of technology in conservation biology is rapidly growing and becoming more widespread (Joppa 2015; Pimm et al. 2015; Berger-Tal and Lahoz-Monfort 2018; Toivonen et al. 2019). Mobile app-derived data, for instance, are increasingly used to provide information for management strategies related to outdoor recreational use and planning, such as hiking and nature-based tourism (e.g. Wood et al. 2013; Fisher et al. 2018). This wealth of new data allows practitioners to map human recreational activities and relate individual behaviour to real-world conditions (Levin et al. 2017; Hausmann et al. 2018). For example, digital footprints in the form of geotagged photographs proportionally reflect human visitation rates at freshwater lakes and reservoirs (Keeler et al. 2015). However, broader incorporation of these data formats into freshwater management remains limited and user-generated data continue to be under-utilised in scientific studies (Venturelli et al. 2017).

Recreational freshwater fishing generates significant net economic benefits in the United States and Canada by engaging over 30 million participants annually, whose equipment and trip expenditures total in the tens of billions USD each year (U.S. Department of the Interior 2016; Fisheries and Oceans Canada 2019). However, high rates of participation in fishing have significant social, ecological and economic consequences. Anglers have repeatedly been implicated as vectors of non-indigenous species by entraining organisms in bait buckets, on fishing lines and on boat motors, hulls and trailers (Rothlisberger et al. 2010; Drake and Mandrak 2014; Smith et al. 2020). Insufficient gear-cleaning allows hitchhiking invaders to be moved overland between water-bodies, promoting both their initial introduction into new catchments and secondary spread into adjacent lakes and reservoirs (Anderson et al. 2014). Angling activity frequently moves invasive species over short distances, but can also distribute them across regions and nations via jump dispersal (Buchan and Padilla 1999; Wilson et al. 2009). In North America, higher numbers of non-native species have been found to coincide with areas of greater recreational fishing demand (Davis and Darling 2017). Examples of ubiquitous nuisance species whose translocation has been partly attributed to angling and boat movements include zebra mussel *Dreissena polymorpha*, Eurasian milfoil *Myriophyllum spicatum*, spiny water flea *Bythotrephes longimanus* and rusty crayfish *Orconectes rusticus* (Lodge et al. 2000; Minchin et al. 2003; Rothlisberger et al. 2010; Kerfoot et al. 2011).

Mobile technologies provide new opportunities to understand angler movement behaviour in ways that have traditionally challenged researchers. Emerging methods for tracing angler movement include trip logs on online fishing forums and mobile applications, remote traffic counters, geocoding wildlife recreational licences, text and data mining of social media and personal fishing gear with enhanced technological capabilities (e.g. Martin et al. 2014; Mogollón and Villamagna 2014; Papenfuss et al. 2015; Monkman et al. 2018; van Poorten and Brydle 2018). These new mobile-based data offer prospects for more robust spatiotemporal estimation of angler activ-

ity (Venturelli et al. 2017). This contrasts with conventional approaches that rely on in-person surveys at boat launches and mail-in questionnaires to licensed anglers and thus only provide a limited snapshot in time of angling activity at a particular location (Rothlisberger et al. 2010; Anderson et al. 2014). Moreover, the shift in demographics of recreational fishing towards younger and more technologically savvy anglers (Recreational Boating and Fishing Foundation 2018) suggests that mobile-based data may shed novel insights into the movement behaviour of individuals who are less likely to engage with long-standing survey instruments.

Given the pivotal role anglers play in transporting harmful freshwater invasive species, understanding when and where fishing activity occurs is critical for providing information for more strategic preventative measures (Muirhead and MacIsaac 2005; Vander Zanden and Olden 2008). Human transportation networks determine the large-scale geographic pathways available to anglers and, hence, the routes by which invasive species may hitchhike between water-bodies. Preventative measures are placed adjacent to these pathways and at the water-body access points they connect (Drake and Mandrak 2010; Meekan et al. 2017). Joining angler movement data with existing invasive species distributions allows for the identification of invasion hubs – areas from which non-indigenous species are frequently moved into nearby locales (Muirhead and MacIsaac 2005; Stewart-Koster et al. 2015). Enhancing our knowledge of human movement behaviour will improve our ability to deploy vector management and prioritise locations for a suite of preventative approaches, including early detection monitoring at access points, roadside boat and gear inspection stations and education in the form of billboards and awareness signs (Sharp et al. 2017; Cimino and Strecker 2018; Reaser et al. 2020).

The potential for invasive species introduction into new water-bodies via angler-driven vectors is constrained not only by the spatial distributions of nuisance species and angler movement, but also by those factors that influence survival during transport, such as species' desiccation tolerance (Havel 2011; Wood et al. 2011; Leuven et al. 2014; Coughlan et al. 2018). Thus, it is important to account for the duration over which angler movement occurs across the landscape after potential entrainment of non-indigenous propagules in an angler transportation pathway (Johnson et al. 2001). In comparison to recreational boaters, anglers may enhance the likelihood for dispersing aquatic invasive species as they are more capable of accessing smaller water-bodies in remote locations (Drake and Mandrak 2010). Previous studies, however, have been unable to account for time when assessing risk of invasive species' introduction and spread via angler movement because such fine-scale data are not generated from conventional survey approaches. Consideration of the temporal dimension of angler movement provides greater resolution into this invasion vector by allowing for explicit consideration of movement events that are shorter in duration and likely to entrain viable propagules (Jerde et al. 2012; Banha and Anastácio 2014). Additionally, this approach has the advantage of integrating species-specific information (i.e. desiccation tolerance) into vector-based invasive species risk assessments.

In this study, we demonstrate how large-scale angler movement behaviour – a major contributor to the spread of invasive species – can be estimated from data col-

lected by mobile fishing technology. Specifically, we used angler location data from ReelSonar's iBobber – a sonar-enabled castable fish-finder with over 5,000,000 georeferenced global records of fishing activities uploaded since the device's launch – to analyse spatial patterns in angler movement across the continental United States. iBobber devices passively collect data upon submersion in water and, thus, have the advantage of representing all angling activity regardless of whether a user actively records a fish catch. Our objectives were to assess the geography of angler activities and movement dynamics while explicitly accounting for spatial distributions of aquatic nuisance species and limitations on propagule viability between water-bodies according to species' desiccation tolerance. The findings of this research offer novel insights into spatiotemporal patterns of angler behaviour and carry important implications for predicting and preventing future transmission of aquatic invasive species via recreational fishing.

Methods

iBobber technology and data processing

iBobbers are small castable, personal fish-finders that sync through Bluetooth with a smartphone application to provide users with real-time information on fish and vegetation presence in the water column, map water-body depth and estimate water and air temperature, wind speed and direction and a suite of additional weather variables. iBobber users include shore-based anglers and those fishing from kayaks, canoes and other boats. iBobbers (distributed by ReelSonar of Seattle, WA) are widely available for purchase in stores and on the web and are primarily used in North America, Europe and east Asia.

Anonymised data were acquired from all iBobber devices that were used over a two-year period (January 2017 – December 2018). When submerged in water, each bobber records a "hotspot" of its geographic location in 30-second intervals, along with time, date, fish presence, depth and a host of other variables. Each device is identified by its unique bobber ID code and iBobber users can view these metrics in real-time using the iBobber phone app. As owners often test their devices initially in their home sinks and pools, we first filtered the data spatially by excluding hotspots that were located outside of a 50-m buffer of the > 379,000 lakes and reservoirs contained in the National Hydrography Dataset, v2 (NHD) for the continental U.S. (U.S. Geological Survey 2018). Timestamped locations were then compiled into single fishing trips by pooling hotspots with the same bobber ID, water-body and date.

Angling trip and water-body metrics

We calculated summary metrics to describe angler fishing activities according to iBobber records, including the number of trips (i.e. distinct visits to a water-body in time)

by each user, total trips per month and day of the week across all water-bodies and users and density of trips (# km^2) across the continental U.S. Water-body characteristics were obtained from the EPA's LakeCat Dataset, which classifies lakes and reservoirs within the NHD by surrounding land use and lithography, size, surface area and additional variables (Hill et al. 2018). We compared the percent urban land cover in the contributing basin of water-body and the maximum depth and surface area of water-bodies fished by iBobber users to that of all water-bodies within LakeCat using a parametric comparison of means according to a two-sample Z-test. In addition, we identified which lakes were reservoirs with USGS' Reservoir Morphology Dataset (Rodgers 2017), compared the likelihood of natural lakes and reservoirs being fished by iBobber users with a two-tailed chi-squared test of independence and assessed the effect size of this likelihood using the odds ratio.

Angler movement events and duration between water-bodies

Least-cost ground transportation distances between consecutive anglers' trips to water-bodies were determined by routing angler locations through GraphHopper's route optimiser, which uses OpenStreetMap as a base map. This is termed an angler (inter-water-body) movement event. GraphHopper routes geographic coordinates through the closest road access point for each water-body, thus most often estimating the transportation distance between public boat launches. We calculated the duration of each angler movement event as the number of days between consecutive trips by iBobber users. Furthermore, we conducted a literature search to identify all nuisance freshwater invasive species with reported tolerated exposure to desiccation (the length of time) in an overland vector, resulting in values for hydrilla *Hydrilla verticillata* (16 hours: Barnes et al. 2013), Eurasian milfoil (2 days: Barnes et al. 2013), New Zealand mudsnail *Potamopyrgus antipodarum* (3 days: Havel et al. 2014), zebra mussel (5 days: Ricciardi et al. 1995), Asian clam *Corbicula fluminea* (23 days: Collas et al. 2014) and Chinese mystery snail *Cipangopaludina chinensis* (63 days: Havel et al. 2014). We then calculated the number of movement events that fell within each species desiccation tolerance range. Lastly, we visualised a subset of angler movements in a region of Wisconsin, U.S. to demonstrate high traffic road routes utilised by anglers and to assess the frequency of movements from non-invaded to invaded water-bodies. We first determined whether angling was a potential vector for a range of invasive species using the USGS Nonindigenous Aquatic Species database (2018) and then classified invaded water-bodies within the angler movement subset as those containing at least one of the identified species (Asian clam, banded mystery snail *Viviparus georgianus*, curly-leaf pondweed *Potamogeton crispus*, Chinese mystery snail, Eurasian milfoil, flowering rush *Butomus umbellatus*, purple loosestrife *Lythrum salicaria*, ornamental water lilies *Nymphaea* sp., rusty crayfish, spiny water flea, zebra mussel) according to presence/absence records from the Wisconsin Department of Natural Resources (2016).

Comparison to other angler participation data

We evaluated the correspondence of angling activity, based on iBobber data with existing creel-based data collected at the scale of individual lakes and states of the U.S. The lake-level analysis obtained data from a state-wide survey of lake users on 86 lakes in Iowa over 5 years (2002–2005 and 2009) (Evans et al. 2009), which we compared with the proportion of trips by lake according to iBobber activity. The state-level analysis compared the percent distribution of annual fishing trips by state reported in the U.S. Fish & Wildlife Service's (USFWS) 2011 National Survey (U.S. Department of the Interior et al. 2011) to the calculated percent of trips made annually to each state by iBobber users. Great Lakes trips were attributed to the state with the nearest shoreline to the trip's coordinates, but North Dakota was excluded as the state did not report data for the 2011 survey. Both lake- and state-level comparisons were measured by the Pearson correlation coefficient. All spatial analyses were completed in ESRI ArcMap version 10.0 (Redlands, CA) and all statistical analyses were completed in R 3.5.1 (R Core Team).

Results

An extensive geographic footprint of angler activities exists across the continental United States according to 66,918 trips taken by 10,768 iBobber users over a two-year period (Fig. 1A). Angler trips were concentrated in more urbanised regions, particularly in the eastern and western states. As expected, trip frequency peaked during the late spring-early summer months (June-July) and was at its lowest in late autumn-early winter (October-November) (Fig. 1B). Moreover, the frequency of trips on weekends (24%) was more than double that of midweek days (Fig. 1B inset). Over half (55%) of iBobber users made more than one trip during the study period (Fig. 1C), up to a maximum of 88 trips.

During the study period, iBobber users visited 20,049 different water-bodies, of which 46% were visited more than once (Fig. 2A). The most-visited water-body was Lewisville Lake – one of the largest lakes in north Texas – with 427 trips by 128 different anglers. Water-bodies fished by iBobber users were characterised by having statistically significant higher mean catchment urbanisation (24.3% vs. 9.4%, $z = 3.02$, $p = 0.001$), maximum depth (8.4 m vs. 2.6 m, $z = -2.01$, $p = 0.022$) and surface area (18.3 km^2 vs. 0.65 km^2, $z = -2.31$, $p = 0.011$) compared to all 379,090 water-bodies across the continental United States. iBobber users were over five times more likely to make a trip to reservoirs compared to lakes (two-tailed χ^2, df = 1, $p < 0.001$, logistic regression odds ratio = 5.68).

Anglers engaged in wide-ranging travel distances and durations amongst fished water-bodies. According to 23,363 movements between two successive water-bodies by iBobber users, mean and median road distance travelled was 93 km (SD = 277 km) and 23 km, respectively, ranging from short-distance movements of < 1 km to long-distance movements of ca. 300 km (Fig. 2B). The GraphHopper routing algorithm

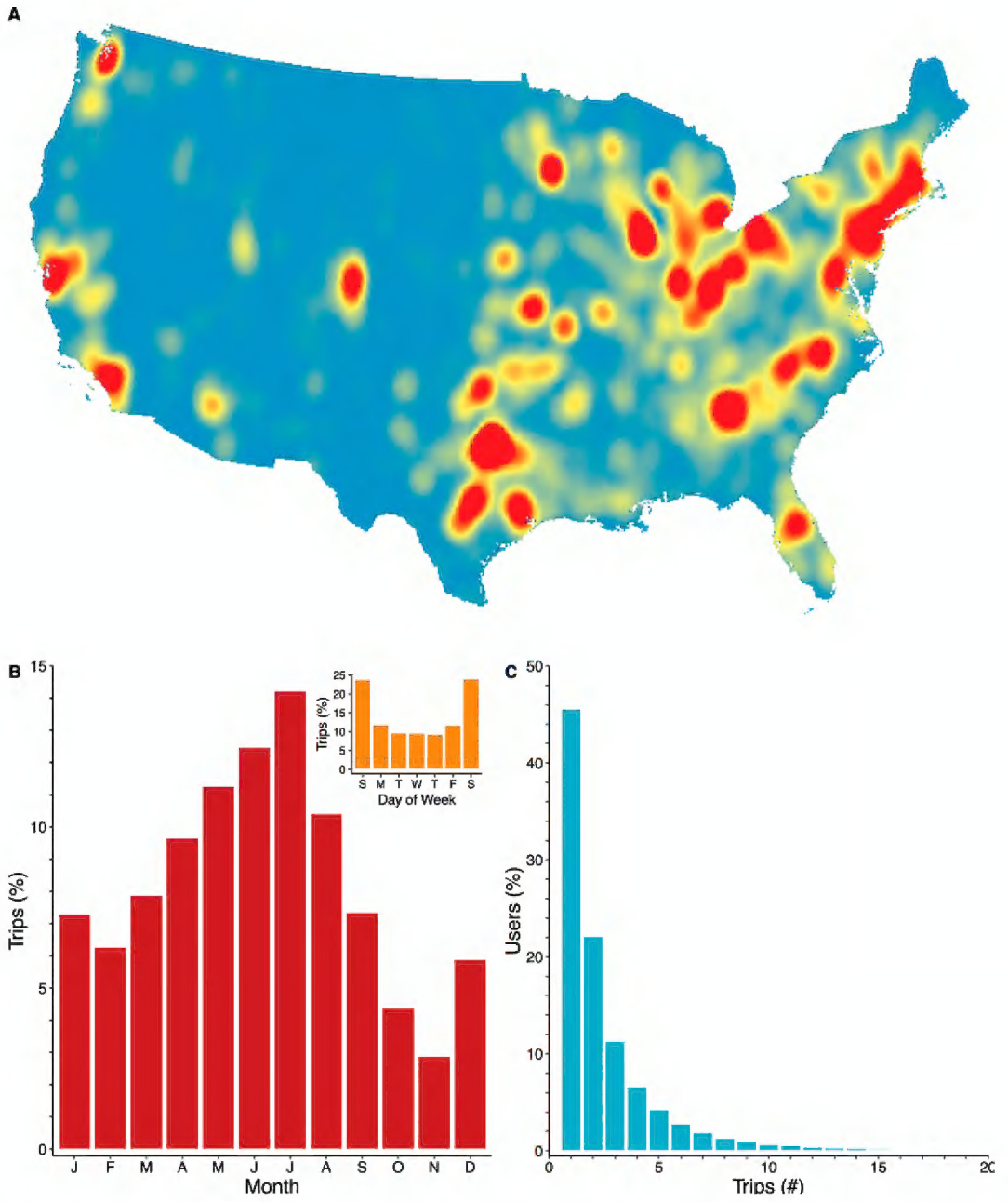

Figure 1. From January 2017 through December 2018 **A** trip density across the continental U.S. ranging from zero (blue) to 1,523 (red) trips per km^2 **B** percentage of trips by month and **(inset)** day of the week and **C** iBobber users (%) by total number of trips taken, truncated at 20 trips (bin size =1).

returned a road distance of zero for 7% of inter-water-body movements (N = 1,677 movements), indicating users walked between water-bodies or travelled on roads not contained in the Open Street Map data layer. Nearly half of inter-water-body movements by iBobber users occurred over a timespan of two days or less, which falls well within the desiccation tolerance window of many prevalent invasive species (Fig. 3). For example, the literature search for invasive species' desiccation tolerance revealed the species with the shortest and longest quantified desiccation tolerance was Hydrilla (16 hours) and Chinese mystery snail (63 days), respectively (Barnes et al. 2013; Havel et al. 2014). This results in 32% (Hydrilla) to 89% (Chinese mystery snail) of all inter-lake movements having a duration that falls within the range of desiccation tolerance.

Estimates of angler visitation frequency, according to iBobber user records, corresponded with previous estimates according to creel surveys. Lake-level visitation by iBobber users was correlated with surveyed visitation of Iowa lake users (R^2 = 0.425,

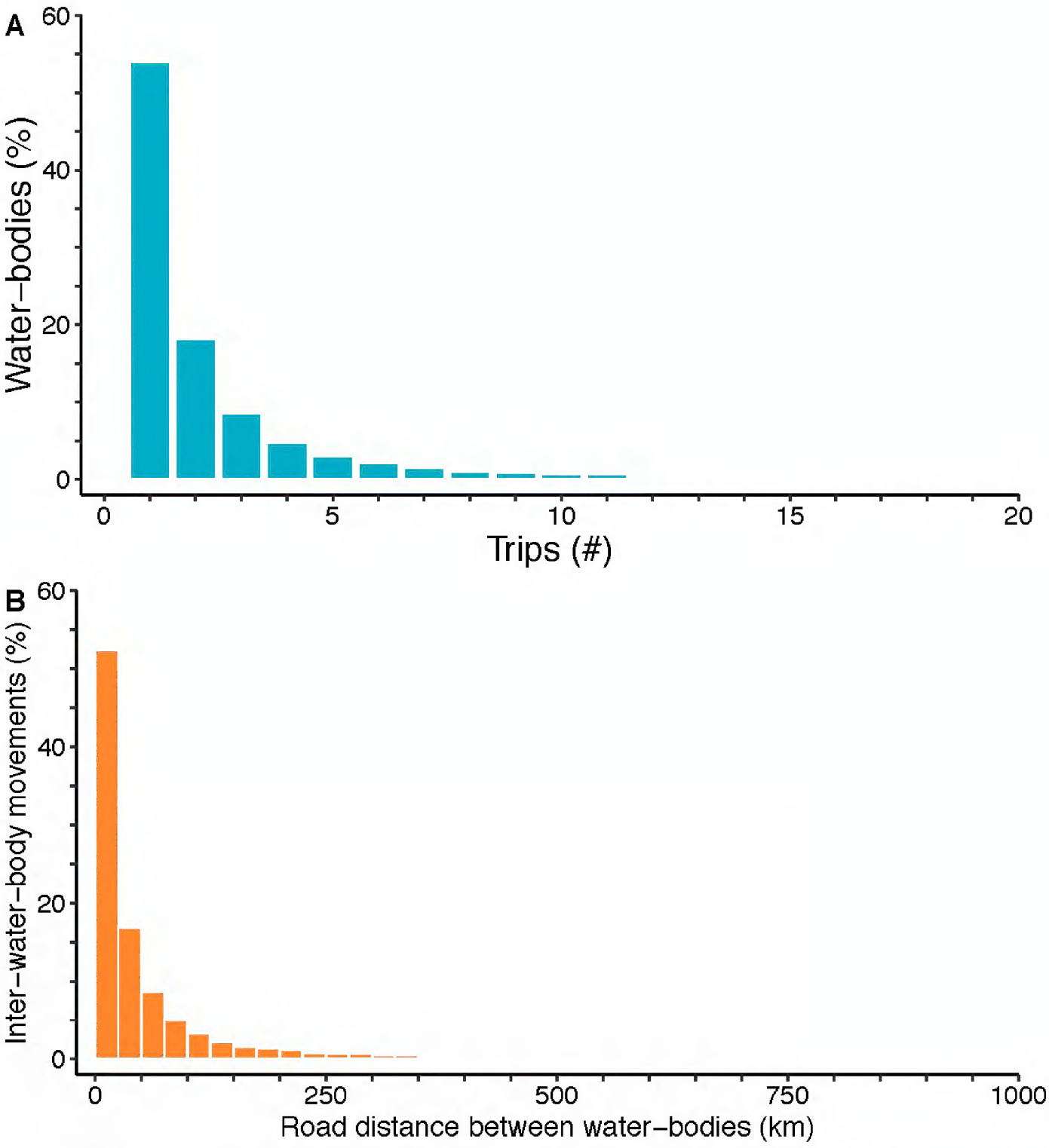

Figure 2. A Percentage of water-bodies according to the number of trips taken by iBobber users, truncated at 20 trips (bin size = 1) and **B** the frequency (%) of movements between two subsequently visited water-bodies by road distance (km) (bin size = 25), truncated at 1,000 km.

$p < 0.001$, $N = 53$) (Fig. 4A). Similarly, for the continental United States, the state-level visitation frequency by iBobber users was positively correlated with relative angling activity by state reported in the most recent USFWS National Survey ($R^2 = 0.342$, $p < 0.001$, $N = 47$) (Fig. 4B). Amongst states, Texas had the greatest disparity between percentage of angling activity in the iBobber (11.6%) and USFWS (5.5%) datasets.

The utility of data from mobile fishing apps to elucidate regional-scale angler movement behaviour was demonstrated using water-bodies around Milwaukee, WI (Fig. 5). For 29 water-bodies, we observed 50 angler trips along 41 visualised road routes – demonstrating the diffuse geographic routes by which non-native species could be

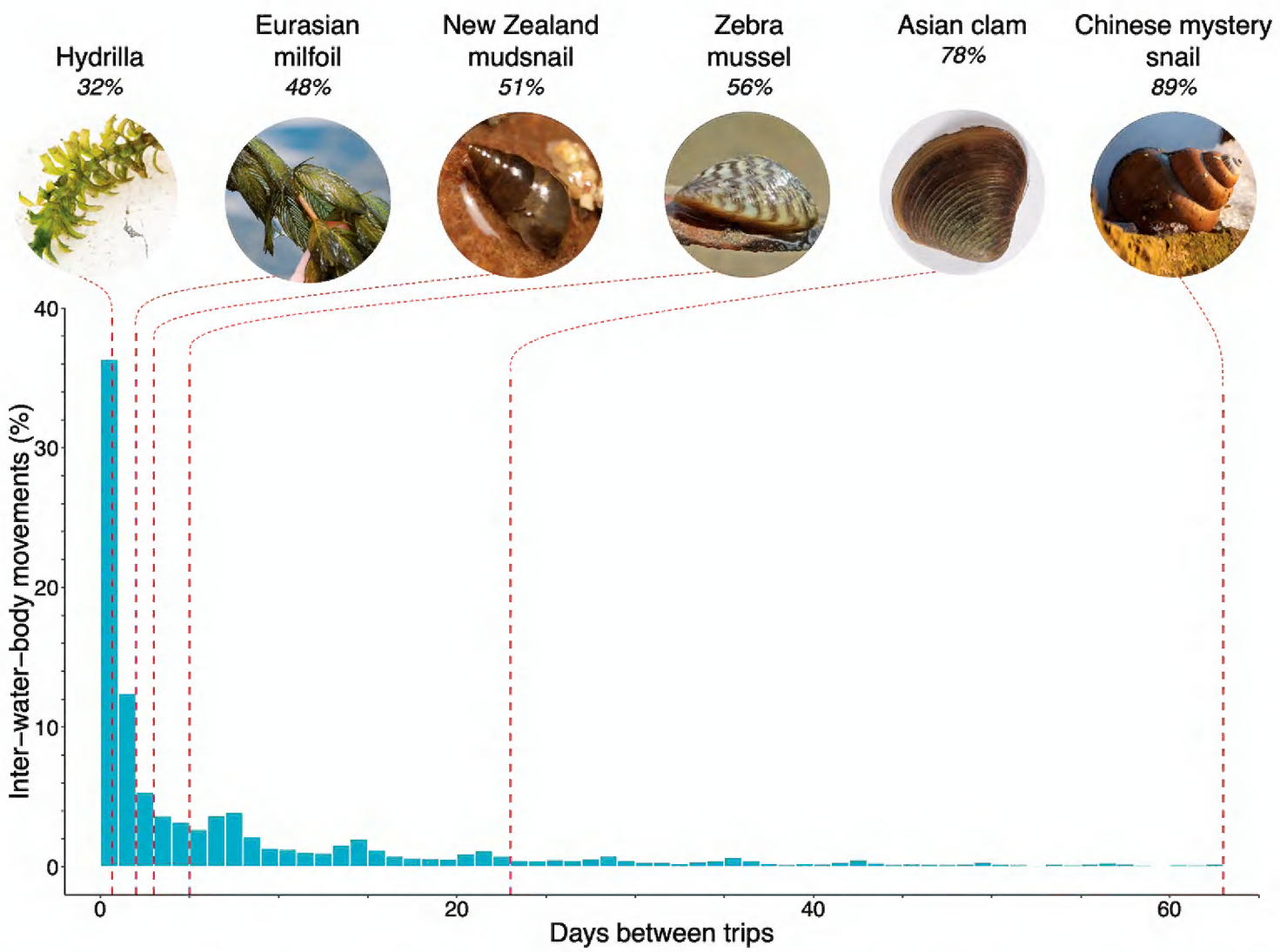

Figure 3. Percentage (%) of iBobber user movements between water-bodies according to the number of days between trips. Vertical lines represent published estimates of survival time when exposed to desiccation in an overland vector for indicated invasive species (% of total movements stated). Photo credits: "Bay grasses on the Susquehanna Flats in Harford County, Md." by chesbayprogram is licensed under CC BY-NC 2.0, "Eurasian Watermilfoil, Susquehanna Flats" by chesbayprogram is licensed under CC BY-NC 2.0, Potamopyrgus antipodarum" by fturmog is licensed under CC BY-NC-SA 2.0, "File:Dreissena polymorpha (Zebra mussel), Arnhem, the Netherlands.jpg" by Bj.schoenmakers is licensed under CC0 1.0, "File:Muschel Aller 7987.jpg" by NobbiP is licensed under CC BY-SA 3.0, "Chinese Mystery Snails in winter" by brentsview is licensed under CC BY-NC 2.0.

transported. Movements tended to originate from a small number of water-bodies (i.e. hubs), with four lakes (Beaver Dam Lake, Lake Monona, Fox Lake, Pewaukee Lake) serving as the origin lake for 64% of movements, which terminated at 20 destination lakes. According to the current distribution of aquatic nuisance species in the region, 100% of angler movements involved visiting an invaded water-body and 8% of movements were from an invaded lake to a non-invaded lake (Fig. 5).

Discussion

Mobile technologies offer new insights into risks of human-assisted transport of aquatic invasive species. Our investigation of user-generated angling data from iBobber users

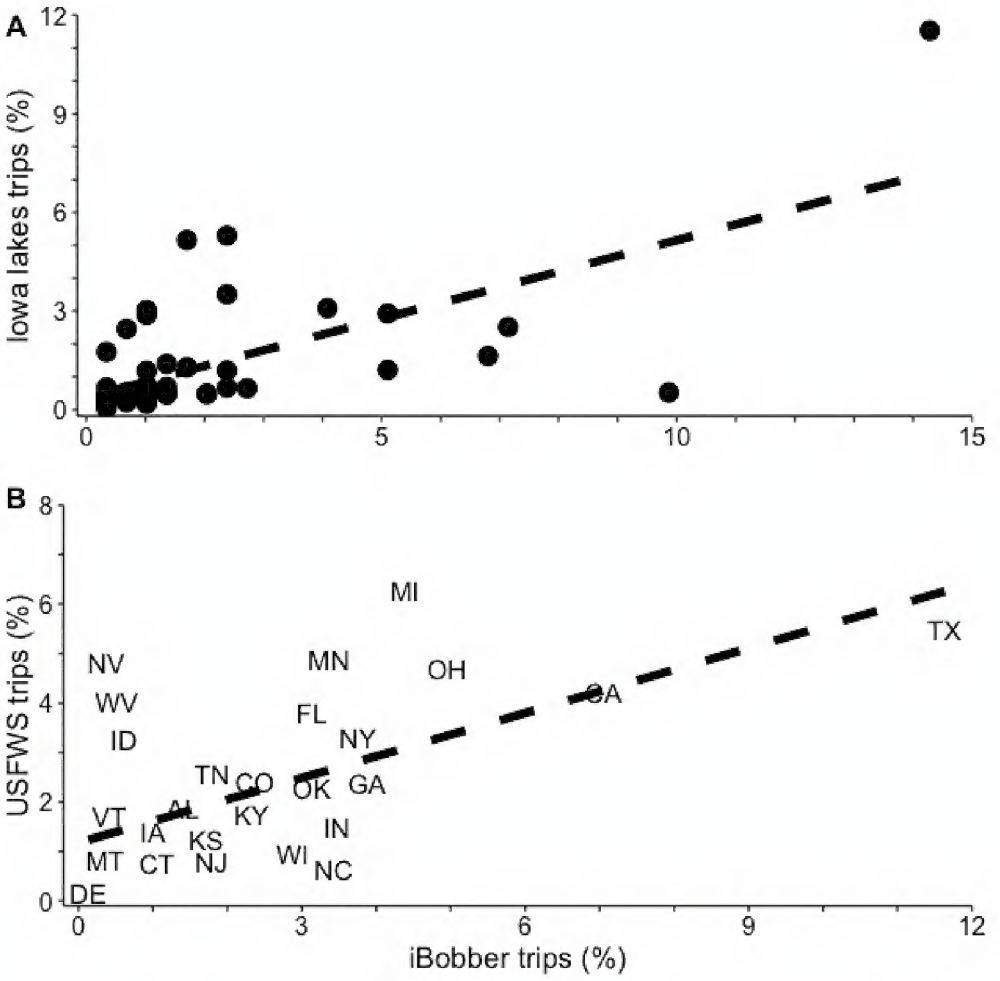

Figure 4. A Total Iowa iBobber user activity by lake (%) versus the total visits by lake (%) as quantified by an Iowa State University state-wide survey ($p = 7.5 \times 10^{-8}$, $R^2 = 0.425$) (Evans et al. 2011) **B** total iBobber user activity by state (%) versus total angling activity by state (%) as quantified by the 2011 USFWS National Survey (U.S. Department of the Interior 2014).

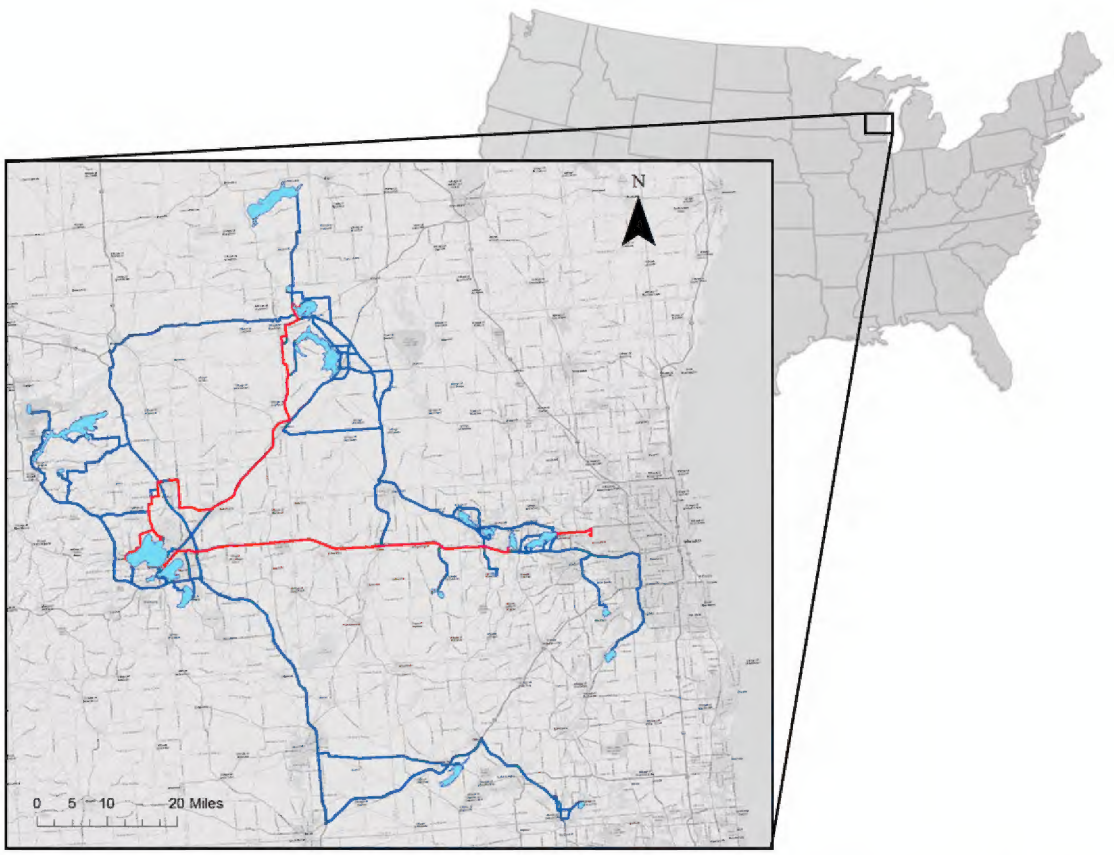

Figure 5. Road-routed movements by iBobber users between lakes in the greater Milwaukee, WI area. Movements between lakes with invasive species present are indicated by blue routes while movements from an invaded lake to a non-invaded lake are indicated by red routes.

across the United States demonstrates the potential to characterise angler site preference and movement activities well beyond the geographical and temporal extent of conventional ground-collected approaches. Furthermore, our mobile data affirms previous observations that fished water-bodies are commonly large, urban reservoirs. Here, we discuss the relevance of our findings for enhanced prevention of invasive species, evaluate the key benefits and challenges of employing new mobile data forms and suggest future steps to enhance the value of mobile data in invasion biology.

User-generated data sources represent a cost-effective means of mapping human geography of interactions with environments (Deville et al. 2014; Toivonen et al. 2019). iBobbers, as well as similar devices and mobile applications, could provide resource managers with information regarding angler traffic at broader spatiotemporal scales than have previously been available (Venturelli et al. 2017). Given the importance of interstate pathways in facilitating transmission of invasive species and waterborne diseases between lake networks (e.g. Buchan and Padilla 1999; Muirhead and MacIsaac 2005; Stewart-Koster et al. 2015), understanding the dynamics of angler movement across traditional jurisdictional boundaries that often serve as spatial limits for conventional creel surveys is vital (Peters and Lodge 2009). Indeed, data that support coordinated management decisions across neighbouring regions are fundamental to successful management of invasive species in complex social landscapes (Epanchin-Niell et al. 2010). We found that the road distance travelled between water-bodies by iBobber users, for example, exceeded estimates for Wisconsin (mean: 93 vs. 34 km: Buchan and Padilla 1999), but was significantly less than Ontario, Canada (median: 23 vs. 292 km: Drake and Mandrak 2010) according to angler surveys.

Use of geotagged angler data from mobile technology allows for seamless cross-referencing of information about angler behaviour with characteristics of source and destination lakes, such as the pool of non-indigenous species available to be entrained into the vector and key environmental determinants of species establishment. For example, by linking to readily-available species distribution databases for a region in Wisconsin, we showed that approximately one-in-ten movements were from lakes containing aquatic invasive species to lakes currently not invaded. For the U.S., we show that the large population of iBobber users fish reservoirs at five times the rate relative to natural lakes, while concurrent research shows that reservoirs are two to 300 times more likely to support established aquatic invasive species (Johnson et al. 2008). Other predictors of angling activity included facility quality (e.g. boat launch presence) and destination size (e.g. lake area), both well-established determinants of site choice in recreational fisheries (Hunt et al. 2019). Taken together, many opportunities exist to integrate angler movement patterns derived from mobile technology with spatiotemporal data describing propagule pressure and factors related to establishment success.

Timestamped mobile-based data offer opportunities to capture the temporal dimension of angler movements across the landscape by estimating the duration of time between visits to water-bodies. As most iBobber user movement between water-bodies occurs over relatively short timeframes, our analysis suggests that a greater diversity of potential hitchhikers transported by users will be viable, according to desiccation

tolerance, upon arrival at a destination water-body. If entrained on angling or boating gear, species with a longer desiccation tolerance, such as the Chinese mystery snail, are more likely to survive and establish (89% of inter-water-body movements taken by iBobber users) than species with shorter tolerances, such as Hydrilla (32% of movements) (Havel et al. 2014). As an aside, our literature search returned robust estimates of temporal limitations on desiccation tolerance for relatively few species, suggesting that further studies are needed to clarify the length of time invasive species can withstand exposure out of water.

Mobile technologies also facilitate road routing of angler movement between fishing locations. Geotagged fishing locations are particularly amenable to this method, because they allow us to identify the most likely access point of a water-body, which determines the direction from which anglers may approach a lake or reservoir. Understanding the spatial configuration of human movement helps identify crucial nexuses across time and space for intercepting hitchhiking invaders. For example, junctions at which frequently-travelled routes between invaded and non-invaded lakes converge can be prioritised for interceptive approaches, such as watercraft inspection stations and recent modelling efforts to optimise the operating times and locations of such stations will benefit tremendously from the fine-scale timing and direction data that mobile sources offer (Fischer et al. 2020).

Angler mobile applications represent a cost-effective approach to understand angler-assisted vectors for aquatic invasive species and, in some instances, as in the case of iBobber, offer an opportunity for passive collection of angler activity data. This offers a number of advantages. First, as younger anglers' participation in fishing increases, mobile platforms offer management agencies an opportunity to outreach and learn more about these demographics, as these are also less likely to engage with mail-in or in-person surveys (Fisher 1996; Recreational Boating and Fishing Foundation Outdoor Foundation 2018; Gundeland et al. 2020). Second, mobile-based data provide information about the movement of a largely unknown group of anglers accessing water-bodies using non-motorised recreational boats, such as canoes and kayaks and who are similarly dispersal vectors for aquatic invasive species (Stasko et al. 2012; Anderson et al. 2014), but are not subject to conventional creel surveys conducted at boat launches. In summary, while prior work has demonstrated that actively collected mobile data (i.e. records of angler presence at a location which must be initiated by the user, such as fishing logs or catch records) generally reflect the spatiotemporal distribution of creel surveys, here we have shown that passively collected data are similarly valuable (Martin et al. 2014; Papenfuss et al. 2015). This is an important distinction, as self-initiated logs of angler presence at a water-body may not include all fished locations (we also recognise that iBobber users may not always use their device). Anglers will likely prefer to record and share trips during which they made a catch and, thus, actively collected data may be prone to success bias.

Though user-generated datasets of angling activity derived from mobile technology successfully address a number of limitations of traditional creel surveys in terms of their spatiotemporal resolution, they may also introduce new biases. In our analysis, slightly more than half of users only used their iBobber on more than one trip during

the two-year period. However, the substantial number of total iBobber users does allow us to infer movement patterns of a large sample population. Angler activity, according to iBobber users, was found to be comparable to estimates according to creel-based data collected at the scale of individual lakes and entire states of the United States. Much like creel surveys, the demographics of users of a particular mobile application or device are also unlikely to be fully representative of the entire population of interest (Hargittai 2015). For example, the cost of a single iBobber starts at 100 USD, thus imposing a socioeconomic filter on which anglers are likely to purchase and use the device. In fact, the number of iBobber users is estimated to represent less than 1% of anglers across the U.S.; this is similar to the proportion of angler populations represented in traditional survey-based approaches. Additionally, iBobber owners must possess a smartphone, because real-time data from an iBobber is communicated to users via the device's associated phone application. Previous work analysing spatial and demographic biases in other social media applications (Twitter) across the US identified a significant positive influence of higher median income, urbanisation, higher proportion of younger residents and higher proportion of minority residents on the frequency of geotagged posts (Malik et al. 2015). Despite these considerations, it is well recognised that conventional approaches are limited by the tendency to: (1) favour surveying anglers of higher economic status who own boats, (2) demonstrate biases in gender, age and location of respondents to mail questionnaires (Dempson et al. 2012), in part because of non-response and recall bias (Tarrant et al. 1993) and (3) potentially measure intended rather than actual angler behaviour (Venturelli et al. 2017). Moving forward, the extent to which demographic biases may influence the conclusions drawn from user-generated datasets about water-bodies remains unclear and should be a priority for future study.

Creel surveys and other traditional data forms continue to be highly valuable sources of information regarding angler movement of invasive species, particularly when implemented by a dedicated team of resource managers and volunteers aiming to intercept identified target species (Cooke et al. 2015). For example, boat inspection station volunteers at a single location can ask boaters which water-body they visited last and cross-reference their responses in databases of invaded water-bodies. However, for the vast majority of water-bodies with limited local funds and resources dedicated to support such intensive outreach efforts, managers working to prevent invasive introductions into an entire state or region may benefit significantly from insights gained from readily-available, even possibly real-time, mobile data. Despite this, such data are often not publicly available and will require data agreements with technology companies. Moreover, even when data are public (e.g. citizen science initiatives), lack of data sharing with larger initiatives and databases continues to pose a barrier to implementation of emerging data sources in research and management (Johnson et al. 2020). The most effective management strategies will couple an appropriate synthesis of traditional and emerging data sources based on the scope and connectivity of target water-bodies, but this will require a significant investment in web infrastructure to collate, update and disseminate disparate data sources and formats.

The ongoing creation of fishing-orientated technology and mobile applications presents an exciting opportunity for collaboration amongst researchers, technology devel-

opers and resource managers. Integration of mobile data into angler network models, for example, could lead to new developments in graph-theory methods to identify the most influential nodes (water-bodies) and edges (pathways between water-bodies) in terms of propagule pressure (Martin et al. 2017), beyond what is currently supported by more limited in-person or mail survey data (e.g. Muirhead and MacIsaac 2005; Stewart-Koster et al. 2015). Ultimately, such network approaches will benefit substantially from incorporation of water-body-level invasive species records to enable identification of movements from invaded to non-invaded water-bodies. Collaborative efforts could also identify long-standing data gaps in understanding angler behaviour (e.g. bait and gear use tendencies) and intentionally request this information in trip logs and user profiles (Venturelli et al. 2017). iBobber users have the option to self-report this information in their application profile, but our analysis of this data revealed that the vast majority leave these fields blank. Application developers often increase platform use through promotional incentives, such as gear giveaways and similar incentives could also be developed to encourage profile completion. Bait and gear use are particularly informative for invasive species prevention, as the pool of potential species moved by anglers is dependent on their gear (e.g. bait buckets) and method (shore versus boat) of fishing (Drake and Mandrak 2014). Incorporating more specific data on the type of fishing engaged in by recreational anglers into our understanding of propagule pressure will allow resource managers to further narrow preventative approaches to target the specific species most likely to be relocated between water-bodies, based on common fishing practices in a given region.

Conclusion

Mobile fishing applications and devices such as iBobber represent a valuable new passively-collected mobile data source which, along with other types of actively-collected mobile data (e.g. Papenfuss et al. 2015), offer new opportunities to provide information about invasive species management, particularly as it relates to propagule pressure from angler behaviour. User-generated, mobile data expand spatiotemporal estimates of angling activity beyond what is possible with traditional creel surveys and potentially minimise survey costs. The future holds many exciting possibilities to incorporate both digital user-generated and ground-collected data into modelled social-ecological systems to guide more efficient and effective invasive species prevention campaigns.

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